

10. DEFLECTING CAVITIES

INTRODUCTION

RF cavities operating in a dipole mode (TM₁₁₀-like) deflect the head and tail of the 2.5 GeV electron bunches to allow for compression of the x-ray pulse in beamline optics. The center of the electron bunch passes the cavities at *zero* phase of the rf field such that the head and tail are deflected in opposite directions, and the center of the bunch experiences no deflection. This introduces a divergence into the electrons within a bunch that is much greater than the opening angle of hard x-ray radiation (the radiation opening angle is 7 μ rad at 1 Å), and the angular divergence of the electrons ($\sim 6.4 \mu$ m) in the undulators.

The deflecting voltage may be specified in terms of the x-ray pulse duration (see Chapter 1-Overview):

$$\sigma_{x-ray} \geq \frac{E}{e V_{\sigma} k_{RF}} \sigma_y^{RF} \sqrt{1 + \left(\frac{\sigma_{r'}}{\sigma_y^{undulator}} \right)^2} \quad (1)$$

where

$$\sigma_y^{RF} = \sqrt{\frac{\sigma_{RF}}{k_{RF}}} \quad \sigma_{r'} = \sqrt{\frac{\sigma_{x-ray}}{L_{undulator}}} \quad \sigma_y^{undulator} = \sqrt{\frac{\sigma_{undulator}}{k_{undulator}}} \quad (2)$$

Figure 10-1 shows the dependence of x-ray pulse duration (plotted as full-width half maximum) on the deflecting voltage for the baseline parameters (beta-function at the cavities $\beta_{RF} = 90$ m, beta-function at the insertion devices $\beta_{undulator} = 2$ m, beam energy $E = 2.5$ GeV, radiation opening angle $\sigma_{r'}$, beam emittance $\sigma = 9.8 \times 10^{-11}$ m, and rf wavenumber $k = 82 \text{ m}^{-1}$).

There is an advantage in operating the deflecting cavities at high frequency, since for a given peak rf voltage the slope of the voltage waveform around zero-crossing phase is proportional to the frequency of the rf waveform. A practical disadvantage of higher frequencies is the increased resistive losses in the superconducting material (the resistive losses scale as frequency squared).

The voltage required for baseline operation at 2 GeV is approximately 6 MV. To obtain an x-ray pulse duration of less than 50 fs for photon energies above 5 keV, with a 3.1 GeV electron beam, requires a deflecting voltage of approximately 8 MV, and to allow overhead for feedback and reliability, the cavity design voltage is taken to be 8.5 MV. Superconducting cavities are a natural choice in obtaining such a large voltage, and the design of a multi-cell structure with large transverse shunt impedance has been developed. A seven-cell π -mode cavity design has been selected. This represents a compromise between a large number of cells to increase transverse shunt impedance and reduce the number of cavities required, and smaller number of cells to minimize the number of cavity modes and potential mode-coupling. The cavity design is similar to a multi-cell deflecting cavity design for the kaon separation project at Fermilab [1].

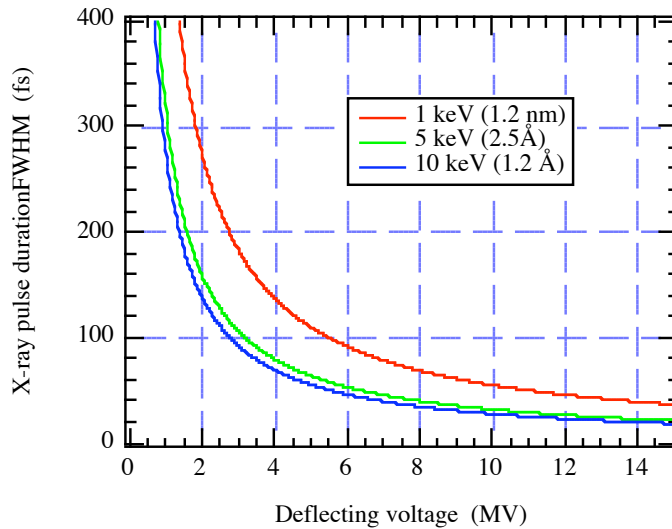


Figure 10-1 X-ray pulse duration as a function of deflecting cavity voltage, for three photon energies, baseline machine parameters.

Figure 10-2 illustrates a typical electromagnetic field distribution of a deflecting dipole mode in a single cell cylindrical pillbox cavity with beampipe, one quarter of the cavity is shown. Preliminary cavity design for the 7-cell cavity has been conducted using the MAFIA and URMEL electromagnetic simulation codes. The cavity operates in a dipole mode with π phase advance per cell. Due to the presence of the beam iris, the mode is not a pure TM dipole mode, but in a hybrid mode consisting of both TM and TE like modes. For the TM_{110} mode in an ideal cylindrical pillbox cavity, a beam travelling on-axis experiences a transverse kick from magnetic forces only. Once the beam iris is introduced, as in the present case, both the magnetic and electric fields contribute to the transverse kick, and the forces add in-phase (provided a π cell-to-cell phase advance).

The TM_{110} -like dipole mode is not the lowest frequency mode in the cavity, and there exists a monopole mode (actually a family of modes for a multi-cell cavity) at a lower frequency. These lower order modes (LOM's) could be excited by beam, and their fields may in turn act back on the beam and introduce energy spread. Damping of the LOM's is required, to a level where energy spread is acceptable.

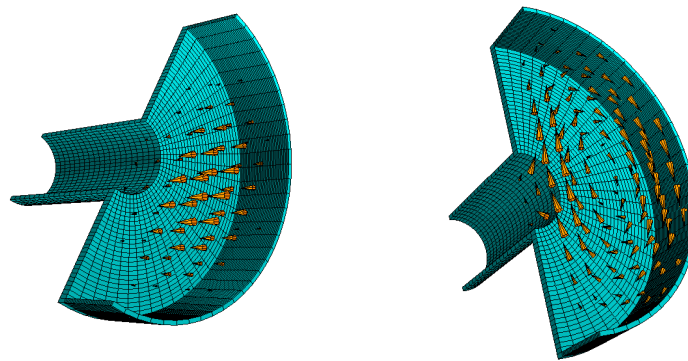


Figure 10-2 Electric (left) and magnetic (right) field distribution of a deflecting dipole mode in a pillbox cavity with beampipes.

To minimize rf power requirements, reduce short-range wake-field effects, and increase the cavity efficiency, 3.9 GHz CW superconducting multi-cell dipole rf cavities have been chosen for this application.

Transverse Shunt Impedance

For the TM dipole mode of an ideal closed cylindrical pillbox cavity, there is no electric field on-axis. Beam going through such a cavity on-axis would experience a transverse force from the magnetic fields only. Once beam irises are introduced, as is necessary for a practical cavity, TE-like modes are introduced in the iris (between cells) and beampipe regions. The deflecting mode is no longer a pure TM_{110} , but becomes a hybrid of TM_{110} and TE_{111} modes in order to satisfy the new boundary conditions introduced by the irises and beampipes. A beam passing through the cavity on-axis will not just experience transverse forces from the magnetic fields, but also from the transverse electric fields near the iris region. For a cavity with π phase advance, these two transverse forces add.

To calculate the impedance of the operating mode of the deflecting cavity, we define the transverse shunt impedance as follows,

$$\left(\frac{R}{Q}\right)_{\perp} = \frac{|E_z(r=r_o) e^{jk_{RF}z} dz|^2}{(k_{RF}r_o)^2 \pi U} = \frac{V_{\perp}^2}{\pi U} \quad (3)$$

$$R_{\perp}^* = \left(\frac{R}{Q}\right)_{\perp} Q \quad (4)$$

where the Panofsky-Wenzel theorem has been applied to obtain the deflecting voltage using the off-axis longitudinal electric fields only. V_{\perp} is the transverse voltage; $\pi = 2\pi f$ with f as the resonant frequency; U the stored energy of the mode at the resonant frequency; E_z the longitudinal electric field, and r_o is the radius at which the longitudinal electric field is integrated along the trajectory z . Note that the definition of transverse shunt impedance is in Ohms, and indicates that the deflecting kick is independent of beam position in the cavity.

PRELIMINARY CAVITY DESIGN

Taking advantage of similarities in requirements with the FNAL design for the kaon separation project [1,2], and crab cavity designs developed at KEK and Cornell University [3], the cavity design was initially scaled from the KEK-B crab cavity geometry, and then extended to a 7-cell structure and modeled using the 3-D MAFIA code.

An initial $(R/Q)_{\perp}$ of 50 Ω /cell was obtained for a 7-cell cavity at 3.9 GHz without optimizing the cavity geometry. The $(R/Q)_{\perp}$ may be further increased by perhaps 10-15% with more thorough cavity geometry optimization efforts, which will be performed with the development of the project.

Simulation Results of a 7-cell Cavity

The electric field distribution of the deflecting mode is shown in Figure 10-3 as the result of a simulation in 2D (r - z geometry) using the MAFIA code. The beam pipe radius at the end cell is enlarged to allow for an input power coupler to be added. The end-cell geometry was adjusted (the cavity gap was shortened, and the radius enlarged) in order to obtain good field flatness. This same MAFIA model has also been used for higher- and lower-order mode calculations.

Based on experimental achievements of superconducting cavity technology, a (somewhat conservative) limit of 5 MV/m gradient in the deflecting field has been chosen, as a result of restricting the critical surface magnetic fields to be around 80 mT, (corresponding to a 25 MV/m acceleration gradient in the TESLA SC cavities). The unloaded quality factor Q_0 is estimated to be 2×10^9 , as measured in tests of a five-cell cavity at Fermilab [2]. Table 1 presents simulation results for one 7-cell cavity.

To obtain the required 8.5 MV deflecting (peak) voltage, seven 7-cell cavities are required with total rf power dissipation of about 20 watts at 2 K. rf power requirements will depend on the coupler, achievable Q_{ext} and control of microphonics, and will be assessed in the future.

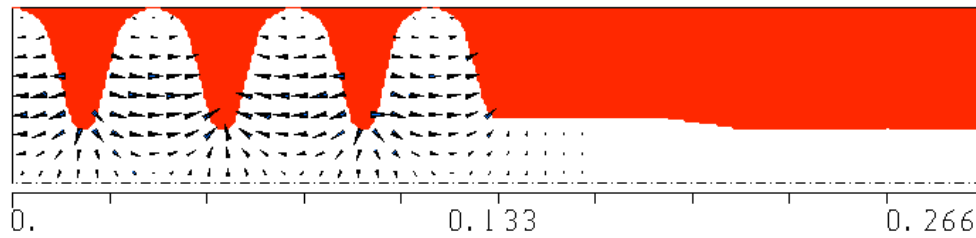


Figure 10-3 Longitudinal electric field distribution of the deflecting mode in the 7-cell cavity at 3.9 GHz. The mode was simulated using the 2D MAFIA code using a symmetry plane to model half of the cavity (3.5 cells).

Polarization of the Cavity

For a perfectly cylindrical rf cavity, there exist a pair of degenerate dipole modes. In order to split the degeneracy sufficiently to avoid coupling between the modes of different polarization, and to orient the required polarization in the vertical direction, the cavity geometry must be perturbed from the purely cylindrical symmetry. We plan to deform the cavity in one plane to achieve these goals, as has been used successfully at KEK and FNAL [2-3]

Table 10-1 Parameters for one 7-cell SC cavity

Cavity frequency	3.9	GHz
Phase Advance per cell	180°	Degree
Cavity Equator Curvature	1.027	cm
Cavity Radius	4.795	cm
Cell length	3.846	cm
Iris Radius	1.500	cm
Beam pipe radius	1.500	cm
TM mode cut-off frequency	7.634	GHz
TE mode cut-off frequency	5.865	GHz
$(R/Q)_\parallel$	350	Ω
Q_0	2×10^9	
Transverse shunt impedance	7×10^5	M Ω
Active cavity length	26.92	cm
Effective deflecting gradient	5	MV/m
Transverse voltage	1.346	MV
Power dissipation at 2 K	2.6	Watts

Higher Order Modes (HOMs) and Lower Order Modes (LOMs)

MAFIA 2D simulations of the 7-cell cavity have been performed to study the higher and lower order modes. Combinations of symmetry and boundary conditions have been applied to simulate all modes below beam pipe cut-off frequencies. Loss factors and shunt impedance of these modes are shown in Tables 10-2 and 10-3. We have assumed Q_0 of 2×10^9 for all modes, with no damping (a worst case estimation). It is worth noting that both longitudinal and transverse HOMs and LOMs will be damped to some extent by the main rf coupler, and further investigation is underway.

Note that the definition of transverse impedance used in Table 10-2 follows the convention used for beam dynamics and instability calculations, in order to take into account the variation in beam-induced signal as a function of transverse offset from the cavity axis. The induced wakefield dependence on transverse offset is included in the expression:

$$R_\perp = \left(\frac{R}{Q} \right)_\perp Q k_{RF} \quad (5)$$

where the units are Ω/m .

A steady state longitudinal voltage, V_{induce} induced by 1 nC bunch at 10 kHz repetition rate is estimated for each monopole mode, and shown in Table 10-3. For the monopole modes, two LOMs dominate, and electric field distributions of these two modes are plotted in Figures 10-4 and 10-5. These two dominant lower order monopole modes must be damped to reduce quality factors to below 10^5 - 10^6 in order to maintain an energy spread of 10^{-4} at 2.5 GeV beam energy.

A 3D MAFIA model with rf power coupler will be built to study the damping efficiency of the coupler on all LOM and HOM modes. A coaxial type LOM damper through the beam pipe, proposed for the KEK-B factory, could be adopted if necessary, but this may increase the complexity and cost of the cavity.

Beam Loading of the Deflecting Mode

Beam passing through deflecting cavity interacts with the cavity, loses energy, and induces a voltage in the cavity. This voltage acts back on the beam and causes energy spread and transverse deflection along the bunch. The beam induced transverse voltage generated in the operating mode may be written as:

$$V_{\perp} = \left(\frac{R}{Q} \right)_{\perp} \frac{Q_o}{1 + \beta} k_{RF} \beta r I \quad (6)$$

where I , βr and β are beam current, displacement from cavity axis and rf coupling constant, respectively, and baseline parameters are $k_{RF} = 82 \text{ m}^{-1}$ (3.9 GHz), $\beta r = 0.1 \text{ mm}$ and $\beta = 26$ (assuming an achievable bandwidth of 50 Hz which corresponds to an external Q of 7.8×10^7). For a beam current of 10 μA in a seven cell cavity, the induced transverse voltage is then 2.1 kV, only 0.18 % of the cavity deflecting voltage of 1.2 MV.

The power induced in the operating mode of the cavity by beam offset 0.1 mm is

$$P = \frac{1}{2} f_{rep}^2 q^2 \left(\frac{R}{Q} \right)_{\perp} \frac{Q_o}{1 + \beta} k_{RF} \beta r \quad (7)$$

or 10 mW, and is small compared with 2.6 watts dissipated in the cavity. The loss factor for the operating deflecting mode is 176 V/(pC m).

Table 10-2 Dipole modes (HOM's) of the 7-cell cavity

Frequency	$(R/Q)_\parallel$	Loss factor	Transverse impedance R_\perp
[GHz]	[Ω]	[V/pC/m]	[M Ω /m]
3.9112	0.3	0.1	4.117×10^4
3.9212	3.0	1.5	4.862×10^5
3.9390	0.2	0.1	4.033×10^4
3.9662	0.3	0.1	4.579×10^4
4.0045	0.3	0.2	5.756×10^4
4.0523	0.0	0.0	1.177×10^2
4.2213	0.2	0.1	3.921×10^4
4.2939	1.2	0.7	2.093×10^5
4.4175	0.0	0.0	1.015×10^3
4.5725	1.7	1.2	3.275×10^5
4.7488	2.7	2.0	5.316×10^5
4.9336	7.8	6.3	1.617×10^6
5.1024	1.2	1.0	2.490×10^5
5.3002	0.3	0.2	5.823×10^4
5.3058	0.1	0.1	1.957×10^4
Sum		13.7	3.720×10^6

Table 10-3 Monopole modes (LOM and HOM) of the 7-cell cavity

Frequency	(R/Q)	Loss factor	Shunt impedance R	Induced voltage
[GHz]	[Ω]	[V/pC]	[M Ω]	[MV]
2.8132	1	0.0038	1,731	0.017
2.8208	1	0.0056	2,507	0.025
2.8321	13	0.0597	26,830	0.268
2.8453	10	0.0427	19,107	0.191
2.8581	284	1.2742	567,621	5.676
2.8685	411	1.8515	821,827	8.218
2.8750	56	0.2546	112,760	1.128
5.7836	0	0.0017	379	0.004
5.8026	0	0.0002	53	0.001
5.8348	4	0.0357	7,783	0.078
5.8797	12	0.1105	23,923	0.239
5.9343	5	0.0498	10,693	0.107
5.9912	0	0.0002	33	0.000
6.0377	0	0.0013	271	0.003
6.6123	2	0.0233	4,496	0.045
6.6135	0	0.0033	633	0.006
6.7391	0	0.0010	185	0.002
6.8025	2	0.0227	4,244	0.042
6.8722	0	0.0037	678	0.007
6.9377	0	0.0048	874	0.009
7.0615	32	0.3507	63,240	0.632
7.5036	10	0.1124	19,077	0.191
7.5093	0	0.0014	243	0.002
SUM		4.2147	1,689,188	16.892

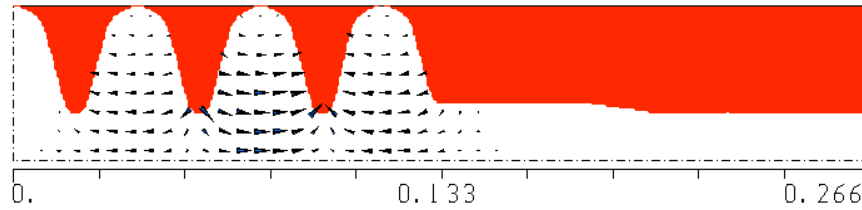


Figure 10-4 Electric field distribution of the monopole LOM at 2.8581 GHz

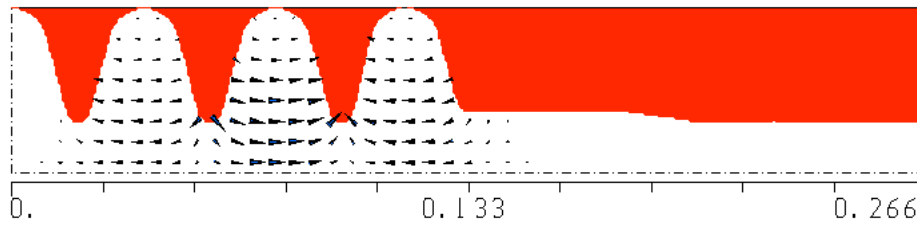


Figure 10-5 Electric field distribution of the monopole LOM at 2.8685 GHz

REFERENCES

- [1] L. Bellantoni, *et al.*, “Design and Measurements of a Deflecting Mode Cavity for an RF Separator.” Proc. PAC2001, Chicago, 2001
- [2] M. Champion, *et al.*, “Engineering, Design and Prototype Tests of a 3.9 GHz Transverse-Mode Superconducting Cavity for a Radiofrequency-Separated Kaon Beam,” Proc. PAC2001, Chicago, 2001
- [3] K. Akai, “Development of Crab Cavity for CESR-B,” Proc. PAC 1993, Washington, May 1993.